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Lawrence Livermore National Laboratory ULTRA-350 Test Bed

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Abstract

LLNL has many in-house designed high precision machine tools. Some of these tools include the Large Optics Diamond Turning Machine (LODTM) [1], Diamond Turning Machine #3 (DTM-3) and two Precision Engineering Research Lathes (PERL-1 and PERL-II). These machines have accuracy in the sub-micron range and in most cases position resolution in the couple of nanometers range. All of these machines are built with similar underlying technologies. The machines use capstan drive technology, laser interferometer position feedback, tachometer velocity feedback, permanent magnet (PM) brush motors and analog velocity and position loop servo compensation [2]. The machine controller does not perform any servo compensation it simply computes the differences between the commanded position and the actual position (the following error) and sends this to a D/A for the analog servo position loop.

LLNL is designing a new high precision diamond turning machine. The machine is called the ULTRA 350 [3]. In contrast to many of the proven technologies discussed above, the plan for the new machine is to use brushless linear motors, high precision linear scales, machine controller motor commutation and digital servo compensation for the velocity and position loops. Although none of these technologies are new and have been in use in industry, applications of these technologies to high precision diamond turning is limited. To minimize the risks of these technologies in the new machine design, LLNL has established a test bed to evaluate these technologies for application in high precision diamond turning. The test bed is primarily composed of commercially available components. This includes the slide with opposed hydrostatic bearings, the oil system, the brushless PM linear motor, the two-phase input three-phase output linear motor amplifier and the system controller. The linear scales are not yet commercially available but use a common electronic output format.

As of this writing, the final verdict for the use of these technologies is still out but the first part of the work has been completed with promising results. The goal of this part of the work was to close a servo position loop around a slide incorporating these technologies and to measure the performance. This paper discusses the tests that were setup for system evaluation and the results of the measurements made. Some very promising results include; slide positioning to nanometer level and slow speed slide direction reversal at less than 100nm/min with no observed discontinuities. This is very important for machine contouring in diamond turning. As a point of reference, at 100 nm/min it would take the slide almost 7 years to complete the full designed travel of 350 mm. This speed has been demonstrated without the use of a velocity sensor. The velocity is derived from the position sensor.

With what has been learned on the test bed, the paper finishes with a brief comparison of the old and new technologies. The emphasis of this comparison will be on the servo performance as illustrated with bode plot diagrams.

Introduction

The ULTRA-350 is a horizontal diamond turning machine. The machine configuration is illustrated in Figure 1. The current machine design uses linear brushless motors for the actuators and high precision 2D linear scales (displacement and yaw) for the metrology sensors. The ULTRA-350 test bed was established to evaluate these technologies for use on the new machine. Previous in-house designed high precision LLNL diamond turning machines have used capstan drives with DC rotary motors as the actuators and Michelson type two frequency heterodyne laser interferometers as the metrology sensors.

The target performance for the new diamond turning machine is 25nm (pv) contouring accuracy and a 1 nm rms surface finish. Active real time control of the tool tip position will be used to achieve the stated accuracy. There are several elements of the machine design that together contribute to the final machine accuracy. Some of these elements include the metrology system, the temperature control system and the servo system. An error budget can be developed to identify the impact of each of these sources. LLNL has high confidence in the ability to obtain very high precision temperature control (0.001 degree C or better) of the machine. As of this writing, the 2D linear scales for the metrology system are being evaluated for the required accuracy. This paper discusses the scales only in the context of motor commutation and machine servo compensation.

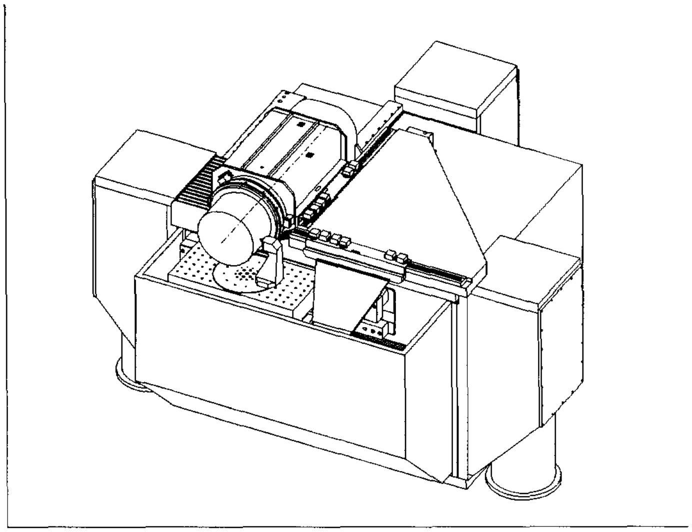

Figure 1. ULTRA 350 Diamond Turning Machine

The primary focus of this paper is to report on how the test bed servo system was setup, tuned and evaluated. The test bed helped answer many questions e.g. 1.) Will a linear motor drive system perform as well as a capstan drive system? 2.) What about the contrast between DC motor self-commutation and brushless motor controller commutation? What about the quality of the velocity feedback provided by a co-located motor tachometer verses velocity derived from only a position transducer? What about the use of a complete digital control system for velocity and position control loops as opposed to an analog only velocity loop and position loop analog compensation with digital command?

Contouring in diamond turning may require axis reversal. In the LLNL diamond turning machines, the analog velocity loop tachometer feedback provides damping and feedback when the rate of the position feedback (from the interferometer) is reduced to near zero. The tachometer loop also solves the problem of magnetomechanical resonance that occurs in capstan slide drive systems using DC torque motors. This effect reduces the torque (force) to velocity loop transfer function gain at frequencies below the resonance for small motor angular displacements (Figure 4 curves A and B). The effect is thought to be caused by the restoring torque when the rotor of the motor takes a magnetic set. The slide mass (M) along with the_ reflected spring stiffness (K) creates the magnetomechanical resonance The resonant frequency is $\sqrt{(K/M)}$. Data from the test bed has demonstrated nanometer level positioning (Figure 6) and extremely low speed (less than 100 nm/min) slide reversal without any observed discontinuities (Figure 5). The test bed high resolution position feedback and the use of controller high resolution sinusoidal motor commutation appears to provide sufficiently smooth slide motion with proper servo system compensation.

The majority of the system dynamics are enclosed in the velocity loop, The last section of this paper contrasts the open loop velocity transfer functions (torque or force versus velocity as a function of frequency) of several of LLNL diamond turning machines to that of the test bed.

Test Bed Components

Figure 2 is an abbreviated block diagram of the ULTRA-350 test bed major components. The test bed is primarily composed of commercially available components. This includes a slide with opposed hydrostatic bearings, the oil bearing pump system, the PM brushless linear motor, a three-phase output, two phase input linear motor amplifier and the controller. The 2D linear scales are not yet commercially available, however for the purpose of this paper the second axis of the scale is not relevant.

From a servo system standpoint, the controller is the heart of the system. It provides the encoder resolution extension algorithm, the commutation algorithm and all the tuning parameters. Additional analog inputs and outputs have been activated as shown on the diagram. These inputs and outputs, when properly scaled can be used with a dynamic signal analyzer (DSA) for the purpose of setting and verifying the servo system compensation. There are several servo configurations that are allowed by this controller. The one shown in Figure 2 is the standard configuration minus feed-forward terms.

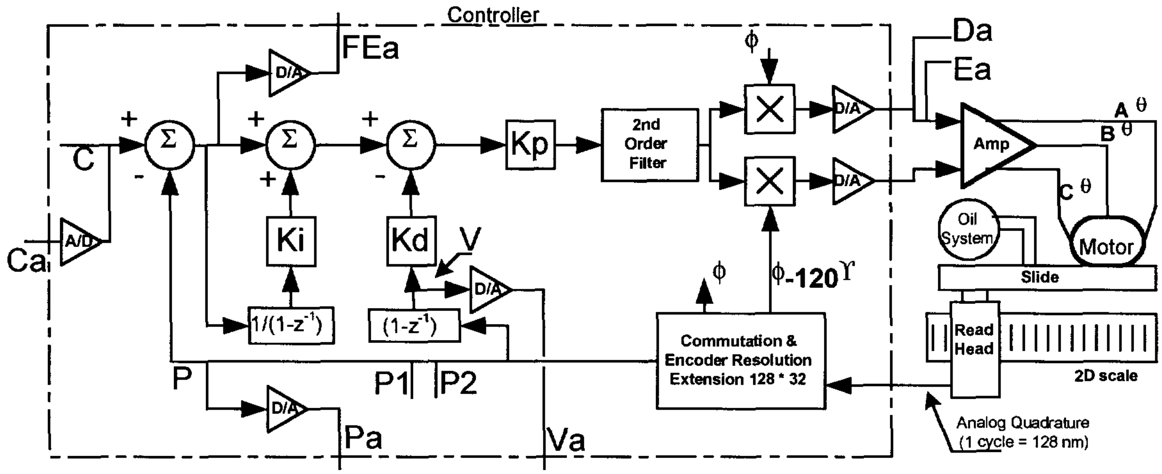

Figure 2. Abbreviated Block Diagram of the ULTRA-350 Test Bed

The amplifier is a linear (non-switching) torque amplifier (transconductance amplifier) with several modes of operation for motor commutation. In this system, the amplifier does not perform motor commutation. The amplifier, with the controller commutation algorithm and the high-resolution encoder feedback, provides the sinusoidal motor commutation. Sinusoidal commutation minimizes motor torque ripple. The amplifier internally develops the third motor phase output from the two input signals.

The motor is composed of a non-contacting forcer coil with rare earth magnet tracks. The ironless nonmagnetic forcer eliminates cogging and magnetic attraction.

The scale is 2D linear scale with 0.5 um line spacing. The read head provides a four times optical extension and generates a sinusoidal quadrature output with a period of 128 nm. The quadrature signal is fed to the controller where the extension algorithm provides for a "whole count" resolution of 1nm and with the 32 count "fractional" extension the position resolution is 0.031nm.

Setup, Tuning and Evaluation

Setup consisted of the necessary mechanical and electrical connections as well as the development of an E-Stop system to protect the operator and equipment of the test bed. A brake can be actuated to hold the slide in position in the event of an E-Stop. In addition, the encoder resolution extension and commutation algorithms and controller variables were setup and initialized.

There are three important loops in the control system of Figure 2. The first is the current loop that is part of the amplifier. The amplifier input voltage is converted to a current. This current is proportional to motor force and hence the motor acceleration. The second is the velocity loop. This loop encloses the third summing junction starting at the input to the gain term (Kp) and continuing through the system to the motor, slide, encoder and back to the negative input of the summing junction. This loop encloses the majority of electrical and mechanical dynamics of the system. It is the phase delay through this loop and the system dynamics e.g. resonances that limit the loop bandwidth. The third is the position loop. It encloses the first summing junction, the velocity loop and completes with the position feedback at the negative input of the first summing junction. The acceleration, velocity and position are the three state variables of this control system. As the acceleration loop is enclosed in the velocity loop and the velocity loop is enclosed in the position loop each of the inner loops must have a greater bandwidth than the outer loops. The approach to servo compensation was to evaluate and or tune each of these loops individually. A dynamic signal analyzer (DSA) was used to accurately measure transfer functions (output/input) of system components and tune the loops. The analyzer provides a plot of gain and phase versus frequency. A bode plot.

The ultimate goal of this control system is to precisely control the position of the slide, reject slide disturbance forces and provide the highest static and dynamic machine stiffness. How well the control system meets the goals is a function of the position loop gain. Generally, loop gain increases at a specific frequency as the unity gain crossover frequency increases or as the loop bandwidth increases. Therefore, the higher the bandwidth, the better the system meets the goals. The acceleration or force loop is the most inner loop of the control system and therefore must have the highest bandwidth. As the motor force is directly proportional to the motor current, the bandwidth of the amplifier current loop is the first limit on system performance.

The amplifier was evaluated by measuring the closed loop transfer function of the output current versus input voltage. A current probe was connected to the A phase output of the amplifier and the input voltage was applied to the corresponding input. The other amplifier input was shorted to ground. (Note the amplifier is not connected to the controller for this test.) The motor is connected as the amplifier load and the slide (or forcer) is locked in place. This measurement indicated a current loop bandwidth of 4 kHz and a peaking in the response of less than 3dB at 2.38 kHz. The phase lag is less than 5 degrees at 300 Hz. This data indicates the amplifier should not limit system performance. Note the amplifier was evaluated at several different drive levels to observe any non-linearity. For example, crossover distortion will appear as a reduction in gain at low drive amplitudes.

The next step was to tune and evaluate the velocity loop. The controller has some auto-tuning capability but the optimum system performance will probably not be achieved with this method. Referring to Figure 2, the controller allows the position loop to be opened between P1 and P2. (The position loop had not been tuned so the loop should be left open at this point.) The open loop velocity transfer function was measured by breaking the loop between Da and Ea and inserting a non-inverting unity gain summing amplifier. The DSA excitation signal is injected at one input of the summing amplifier and the signal at Da is connected to the other input. The open loop velocity transfer function is the ratio of Da/Ea. The tuning parameters Kd, Kp and the 2nd order filter can then be adjusted with complete knowledge of the effects. Note that there are several points to make about this measurement. A.) The velocity loop is actually closed when this measurement is made but the connections to the DSA provide the open loop response B.) The position feedback device is an incremental encoder. Each time the system is started, the controller uses an algorithm that injects current into the motor causing motor motion and allowing the controller to compute the encoder-motor phasing for proper motor commutation. Upon completing this algorithm, the loop closes and the commutation angle is set such that the maximum signal gain is available at Da. It is important that this condition exist in order to achieve the proper loop gain measurement. C.) With this controller topology, the velocity loop gain is a function of Kd, Kp and the 2nd order filter. The initial value or gain for each of these was set to one. The gain of Kp or Kd was then adjusted upward until the DSA indicated the higher frequency resonances would drive the loop unstable. A filter was designed that would attenuate the high frequency resonances and allow an increase in velocity loop gain and bandwidth (Figure 3 curve B).

Figure 3 shows the magnitude of the velocity loop transfer functions. (Note the absolute magnitude of the individual transfer functions are not shown. The curves have been moved vertically to help show the shape of the transfer functions.) Curve A is the measured shape of the open loop velocity transfer function before the filter. Curve B is the 2nd order filter transfer function designed to reduce the frequency components at 700 and 900 Hz and to reduce the peaking at 300 Hz. Curve C is the measured shape of the compensated open loop velocity transfer function. The phase plots are not shown but the loop gain with the filter can be adjusted to provide a velocity loop crossover frequency of about 85 Hz with a 45 degree phase margin. The bandwidth could be further extended if an additional 2nd order filter was available. The current filter contributes almost 18 degrees of phase lag near the crossover frequency to attenuate the peaking at 300 Hz. If an additional filter was available, it could be designed to reduce the peaking at 300 Hz with minimal phase shift at the crossover. This would allow a decrease in the damping of the poles of the first filter and hence an increase the phase margin at the crossover frequency. The loop gain could then be increased increasing the crossover frequency and velocity loop bandwidth.

The position loop is now easy to compensate as the dynamics have been addressed in the velocity loop. Once the proper scaling and offset of the D/A and D/As were set, the open loop position transfer function was found by injecting the DSA excitation signal at Ca and measuring the ratio of Pa/FEa. The position gain is the forward gain Kp. It was changed to increase or decrease the position loop gain but the product of the Kd and Kp must remain constant (the velocity loop gain). The Ki term and the Kp term were adjusted until the maximum crossover frequency could be obtained with a 70 degree phase margin.

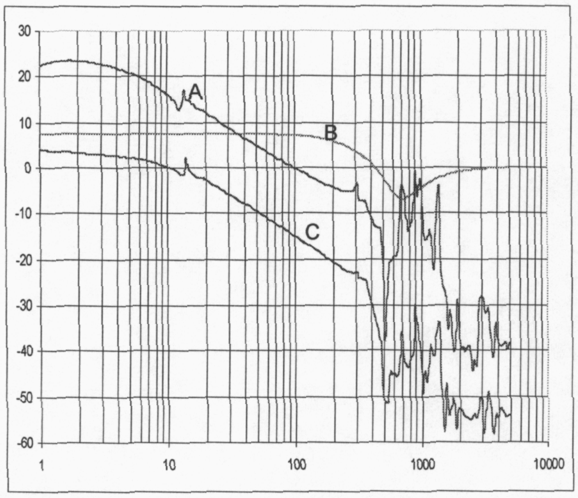

Figure 3. Velocity Loop Transfer Functions (TFs)

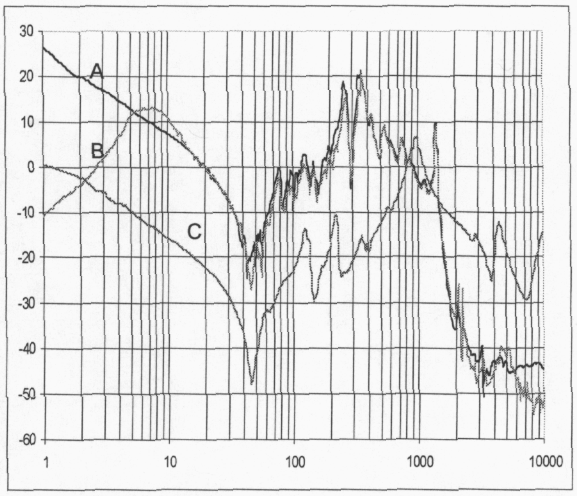

Figure 4. Capstan Drive Velocity Loop Transfer TFs

System Measurement Results

Figure 5 and Figure 6 indicate two important measurements taken from the test bed. Figure 5 is a strip chart recording of position versus time. It is approximately half of an S-shaped curve. Curve A is an analog voltage signal equivalent to the commanded position. Curve B is an analog voltage output signal from an LVDT amplifier with a probe in-line with slide travel. The bandwidth of this signal is limited to 3 Hz. Each horizontal division is 3 seconds. Each vertical division of the LVDT signal is approximately 6.25 nm. The maximum rate of change of the curve is 100 nm/min. The curve clearly indicates smooth slide reversal.

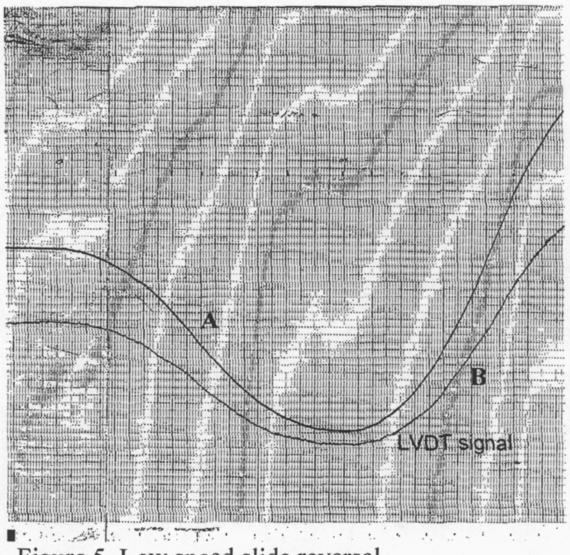

Figure 5. Low speed slide reversal

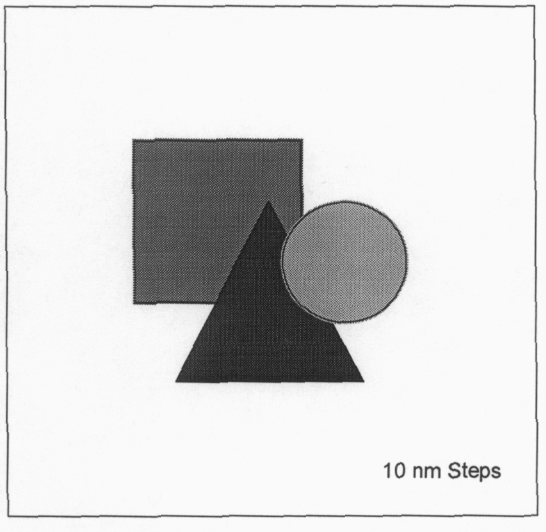

Figure 6. 10 nm steps

Figure 6 is the output of the LVDT when the slide is commanded to move in 10 nm steps. The larger steps in the chart are the inverse of the analog voltage equivalent to the commanded position step. (Only a small part of this signal is shown.)

Technology Comparisons

The dynamics of the open loop velocity transfer function between the linear motor drive system of the test bed and some of the capstan drive machines can be seen by comparing Figures 3 and 4. Figure 3 curve A is the open loop velocity transfer function of the linear motor system before compensation. Figure 4 curve A is the LODTM open loop velocity transfer function before compensation. Figure 4 curve B is also a LODTM transfer function but the curve demonstrates the magnetomechancial resonance that is apparent under small signal conditions. Figure 4 curve C is an open loop velocity transfer function of DTM-3 before compensation. LODTM and DTM-3 are much larger machines than the test bed, however, PERL is a small 100mm diamond turning machine that has a similar characteristic signature of the two larger machine transfer functions. For PERL, the first deep notch is at 200 Hz and the corresponding resonance is at 600 Hz. Although the phase plots are not shown, it should be apparent that the dynamics of the linear motor test bed system are much easier to compensate than the capstan drive system. It also appears that bandwidth for a given system can be much higher with a linear motor drive system than a capstan drive system.

Summary

LLNL in-housed designed high precision diamond turning machines have used capstan drive technology, laser interferometer position feedback, tachometer velocity loop feedback, permanent magnet (PM) brush motors and analog velocity and position loop servo compensation. A new LLNL diamond turning machine is planned that will use brushless linear motors, high precision linear scales, machine controller motor commutation and digital servo compensation for the velocity and position loops. As of this writing, the linear scales are still under investigation for positioning accuracy, however the test bed has demonstrated these technologies will perform as required to meet the new diamond turning machine design goals.

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